Nutrient Recycling Impacts by Zebra Mussels in Harper's Ferry Slough, Upper Mississippi River

by W. F. James, J. W. Barko, H. L. Eakin, J. S. Hendrickson, A. C. Miller, and J. Sauer

PURPOSE: This technical note examines the roles played by zebra mussels in water quality conditions of a backwater region of the Upper Mississippi River, Harper's Ferry Slough.

BACKGROUND: Since the invasion and colonization of zebra mussels in the Upper Mississippi River (UMR) in the 1990's (Cope, Bartsch, and Hayden 1997), concern has grown tremendously over the potential impacts they may have on water quality (James, Barko, and Eakin 1997) and contaminant cycling (Cope et al. 1999), habitat value for other native unionid mussels (Tucker et al. 1993), and fisheries (Richardson and Bartsch 1997). In another riverine environment, the Seneca River (New York), high zebra mussel densities have been associated with a high dissolved oxygen demand, due to respiratory activities, and increased internal recycling of soluble nitrogen (N) and phosphorus (P), due to filtration and excretion (Effler and Siegfried 1994, Effler et al. 1997, Effler et al. 1998). Similar changes induced by zebra mussels in the UMR could have a far-reaching impact on ecosystem dynamics. However, little is currently known about the susceptibility of the UMR to this recent exotic invader. Changes in water quality as a result of zebra mussel activities in regions of the UMR need to be documented in order to better evaluate and predict the overall impact that these changes may have on water quality.

Because rivers have a unidirectional flow, water quality impacts to riverine systems by zebra mussels can be evaluated via input-output analysis (e.g., Effler and Siegfried 1994; Effler et al. 1997). Changes in variables such as dissolved oxygen, chlorophyll, and soluble and particulate nutrient concentrations from inflow to outflow can be converted to areal rates for comparison with rates of filtration and excretion measured for zebra mussels in the laboratory. This study compares budgetary input-output estimates with those estimates determined via previously published laboratory experiments on rates of filtration and excretion by zebra mussels (James et al. 1999) for a backwater region of the UMR, Harper's Ferry Slough. The goal was to quantify impacts of zebra mussel filtration and excretion on water quality dynamics in the slough.

METHODS: Harper's Ferry Slough (Iowa) is a small, narrow channel located in a backwater region of the UMR immediately below Lock and Dam 9. The study area (approximately 2500 m in length and 200 m in width) was located along the western edge of the backwater region in front of the town of Harper's Ferry (Figure 1). The mean and maximum depth within this reach are approximately 0.8 m and 3 m, respectively.

During a period of nominal flow between August and early October 1998, water samples were collected at biweekly intervals in the inflow and outflow of this reach (Figure 1). Total suspended sediment (TSS), filtered onto glass fiber filters (Gelman A/E), was determined gravimetrically after drying at 105 ^{o}C (APHA 1992). Viable chlorophyll *a* (i.e., excluding phaeophytin) was analyzed fluorometrically (Turner Designs model TD-700) according to Welschmeyer (1994) after extraction

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 2000**	2. REPORT TYPE	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Nutrient Recycling Impacts by Zebra Mussels in Harper's Ferry Slough, Upper Mississippi River**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army Engineer Waterways Experiment Station,3909 Halls Ferry Road,Vicksburg,MS,39180-6199**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

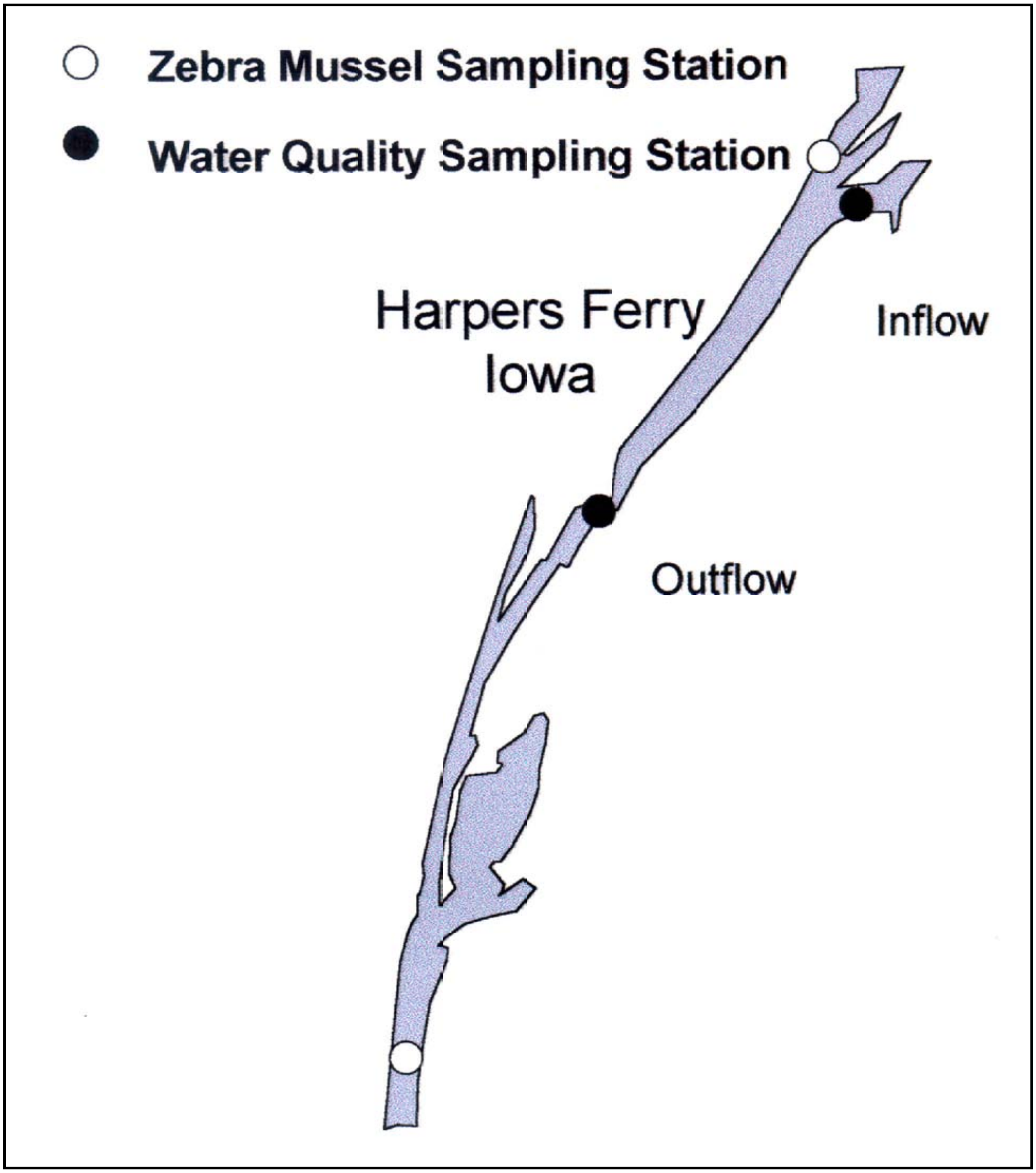


Figure 1. Location of sampling stations in Harper's Ferry Slough

in a 50:50 solution of dimethyl-sulfoxide (DMSO) and acetone. Total nitrogen and phosphorus were determined using automated analytical techniques (APHA 1992; Lachat QuikChem Analyzer, Zellweger Analytics, Milwaukee, WI) after digestion with potassium persulfate (Ameel et al.1993). Soluble reactive phosphorus (SRP), nitrate-nitrite-N (NO_2NO_3-N), and ammonium-N (NH_3-N) were measured using automated analytical techniques (APHA 1992) after filtration through a

0.45-μ filter. Organic nitrogen and phosphorus were calculated as the difference between total and soluble forms. In situ dissolved oxygen and temperature were monitored using a Hydrolab Surveyor 3 which was calibrated against Winkler titrations (APHA 1992). Secchi transparency was determined to the nearest 1 cm using a standard, alternating black and white, 10-cm disk.

A rating curve of flow (cubic meters per second, cms) near the inflow station of the study area (Figure 1) versus stage height in the tailwaters of Lock and Dam 9 was used in conjunction with continuous records of tailwater stage height to estimate daily flow into the slough. Loading and export of chemical constituents were estimated as the product of concentration and daily flow into the study area. Net areal retention or export (mg m^{-2} d^{-1}) was estimated as load minus export divided by the area of the study reach (approximately 350,000 m^2).

Zebra mussel density was determined at two stations (five replicate samples per station) in the slough area in August 1998 (Figure 1). In addition, the length-frequency distribution was determined at each station by measuring to the nearest 2 mm between 300 and 600 individual zebra mussels collected within a quadrat. Density and length-frequency distribution information was used in conjunction with laboratory-determined relationships between zebra mussel length and filtration or excretion (Table 1; see James et al. (1999) for methodological description) to model biomass–specific chlorophyll filtration and excretion of nitrogen and phosphorus (μg/g tissue $mass^{-1}$/h^{-1}) by zebra mussels in the slough. Tissue mass was factored into rate estimations (μg/ $ind.^{-1}$/ h^{-1}) via the following relationship derived from zebra mussels collected in Lake Pepin (Upper Mississsippi River); tissue mass = $0.00017X^2 - 0.00014X$, where X = shell length, mm. Density (ind./m^2) was multiplied by rate estimations to calculate areal rates (mg/m^{-2}/d^{-1}). Densities measured at the two zebra mussel sampling stations were assumed to reflect the average density of the entire study reach in Harper's Ferry Slough and temperatures in the slough (mean = 22.1 °C ± 1 S.E.) were assumed to approximate the temperature in the laboratory filtration/excretion experiments (20 °C; James et al. 1999). These empirical estimates were compared with budgetary estimates to identify possible impacts of zebra mussels on water quality in the slough. Overlaps of the standard deviation between the two methods were compared to make qualitative statements.

Table 1
Relationships Between Zebra Mussel Shell Length (X, mm) and Rates of Filtration or Excretion (Y, μg g tissue $mass^{-1}$ h^{-1})[1]

Variable	Equation
Chlorophyll filtration	$Y = 7224.3X^{-1.82}$
Organic N filtration	$Y = 57071.3X^{-1.97}$
Organic P filtration	$Y = 9814.9X^{-1.06}$
NH_3-N excretion	$Y = 17445.1X^{-2.05}$
SRP excretion	$Y = 333.8X^{-1.06}$

[1] See James et al. (1999) for methodology.

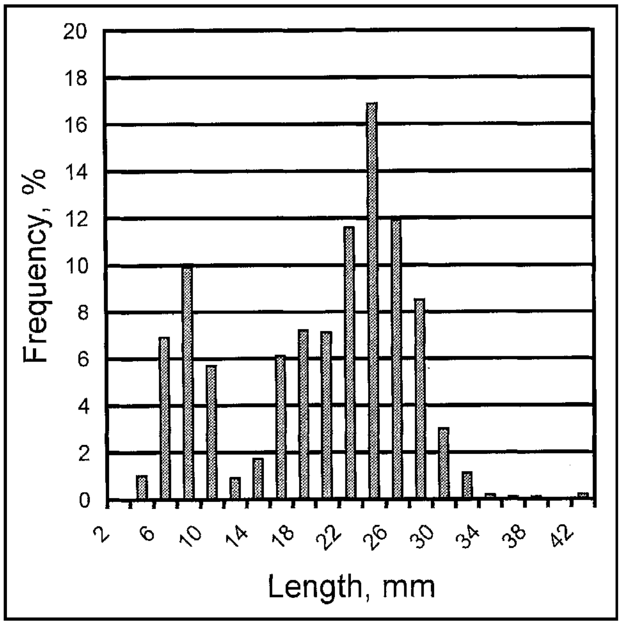


Figure 2. Length-frequency distribution for zebra mussel population in the slough region

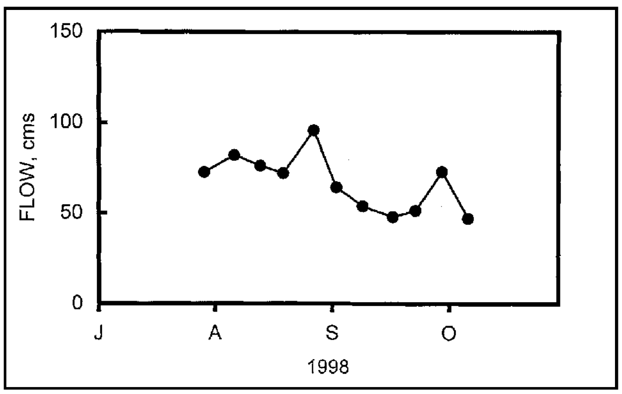


Figure 3. Variations in flow into Harper's Ferry Slough

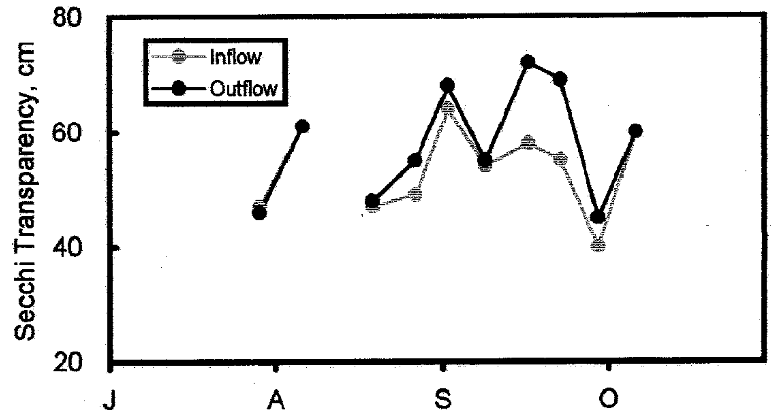
RESULTS AND DISCUSSION: Zebra mussel densities in the Harper's Ferry Slough area (mean = 5,879 ind./m^2 ± 426 S.E.; range = 3,264 to 7,680 ind./m^2) were comparable to densities found in other reaches of the Upper Mississippi River (Cope, Bartsch, and Hayden 1997); but lower by an order of magnitude than densities found in the Illinois River[1] and the Seneca River (Effler and Siegfried 1994; Effler et al. 1997) during the early 1990's. The length-frequency distribution indicated the existence of two cohorts; one clustered near 6 mm and another near 24 mm (Figure 2).

Flow into the slough declined slightly between August and September and ranged between 95.8 cms and 47.3 cms (mean = 66.9 cms ± 5.8 S.E.; Figure 3). Although these flows were probably nominal due to lack of significant precipitation and runoff events during the period, the residence time of the study reach was only approximately 0.15 day. Thus, flushing through the slough was very rapid even under low flow conditions.

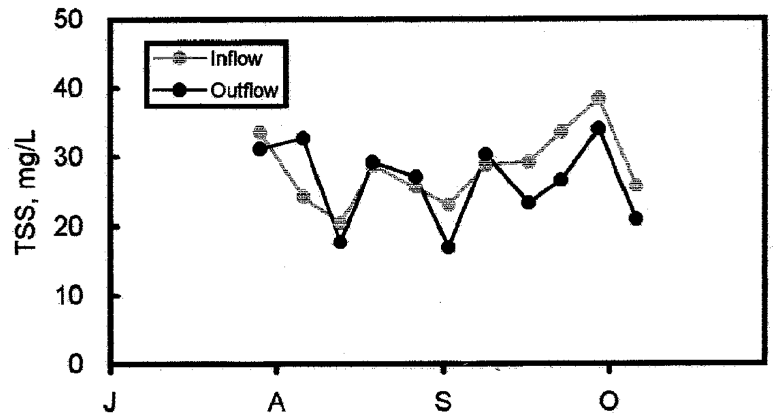
Although Secchi transparency was low (mean = 53 cm ± 2 S.E.; Figure 4a) due to high TSS concentrations in the slough (Figure 4b), a trend of slightly increasing transparency from inflow to outflow was observed, particularly during late August through September (Figure 4a). This pattern coincided with opposite trends of decreasing TSS and chlorophyll from inflow to outflow (Figures 4b and 4c), suggesting some sedimentation and/or filtration of particulate material by zebra mussels. In general, chlorophyll concentrations were high (Figure 4c) in the slough (mean = 30 µg/L ± 6 S.E.; range = 2.8 to 59.2 µg/L), suggesting an abundant food source for zebra mussel filtration. When converted to loading and export rates, changes between inflow and outflow for TSS and chlorophyll were significantly different from zero (comparison of means, t-test; Statistical Analysis System (SAS) 1990), indicating net retention of these particulate constituents within the slough (Table 2).

Like TSS and chlorophyll, organic nitrogen and phosphorus were retained in the slough (Figures 5a and 6a; Table 2). However, there was net export of NH_3-N and SRP from the system (Figures 5b and

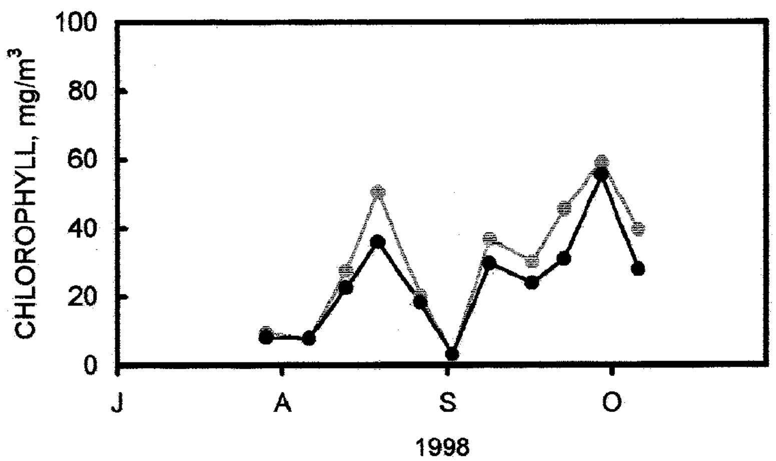
[1] Personal Communication, 2000, K. Douglas Blodgett, Great Rivers Area Director, The Nature Conservancy, Peoria, IL.



a. Secchi transparency



b. Total suspended sediment (TSS)



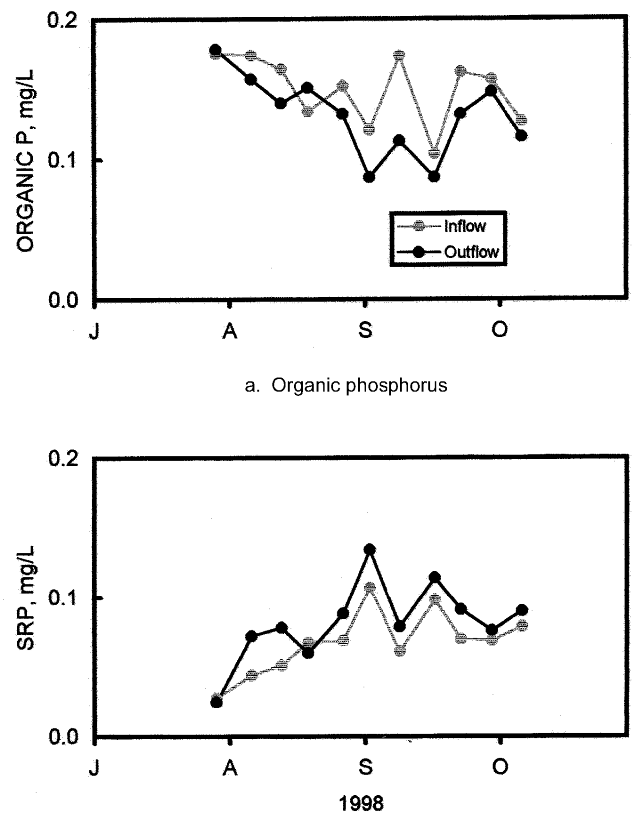
c. Chlorophyll

Figure 4. Variations at the inflow and outflow stations of Harper's Ferry Slough

Table 2
Comparison of Mean External Loading, Net Retention (Positive Number) or Export (Negative Number), and Estimated Zebra Mussel Contribution for Harper's Ferry Slough[1]

Variable	Mean External Load, $mg/m^{-2}/d^{-1}$	Mean Retention Export, $mg/m^{-2}/d^{-1}$	Mean Zebra Mussel Rate, $mg/m^{-2}/d^{-1}$
Chlorophyll	474	89	300
Organic nitrogen	13,267	965	1,435
Organic phosphorus	2,501	284	246
Ammonium nitrogen	932	-123	-867
Soluble reactive phosphorus	1,082	-246	-124
Nitrate-nitrite nitrogen	8,314	-596	-----

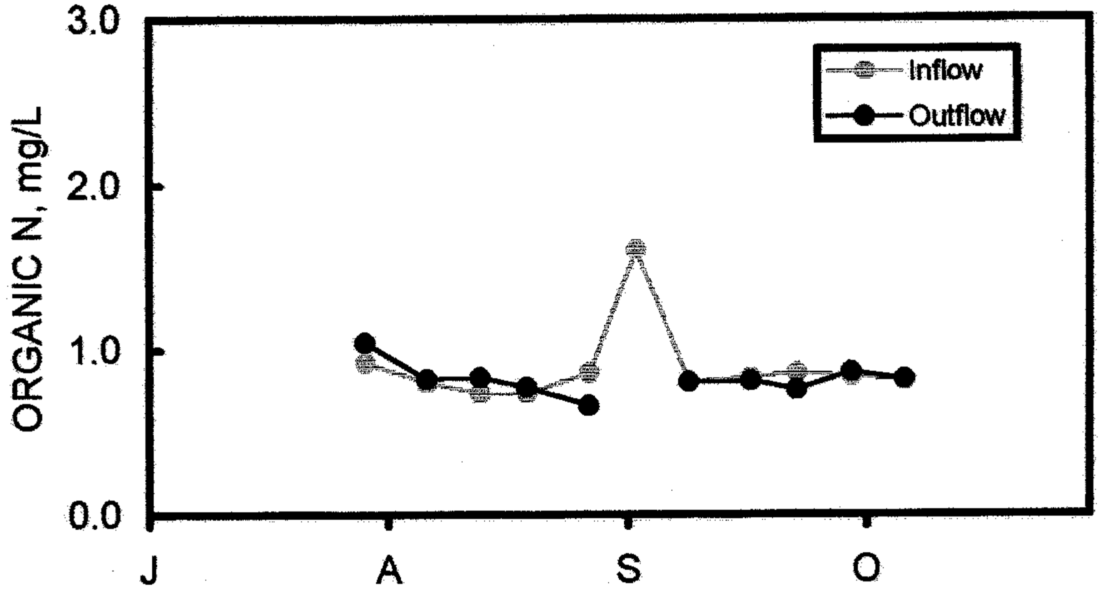
[1] Zebra mussel rates were estimated from laboratory-based experiments described in James et al. (1999). Positive zebra mussel rates represent filtration while negative rates represent excretion. See Figure 7 for statistical information.



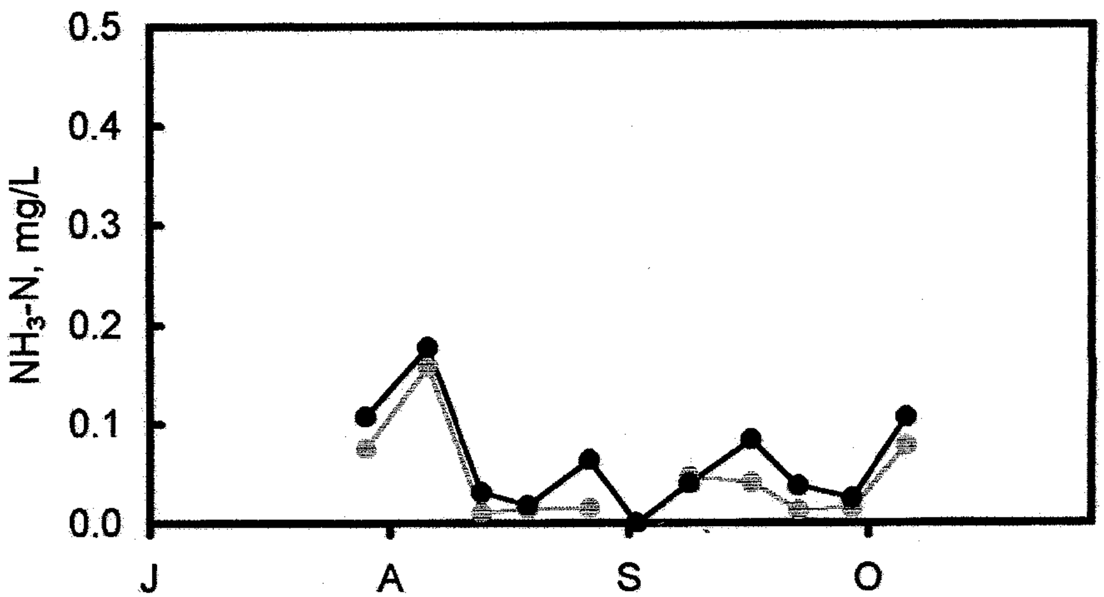
a. Organic phosphorus

b. Soluble reactive phosphorus

Figure 5. Variations in phosphorus at the inflow and outflow stations of Harper's Ferry Slough



a. Organic nitrogen



b. Ammonium-nitrogen

Figure 6. Variations in nitrogen at the inflow and outflow stations of Harper's Ferry Slough

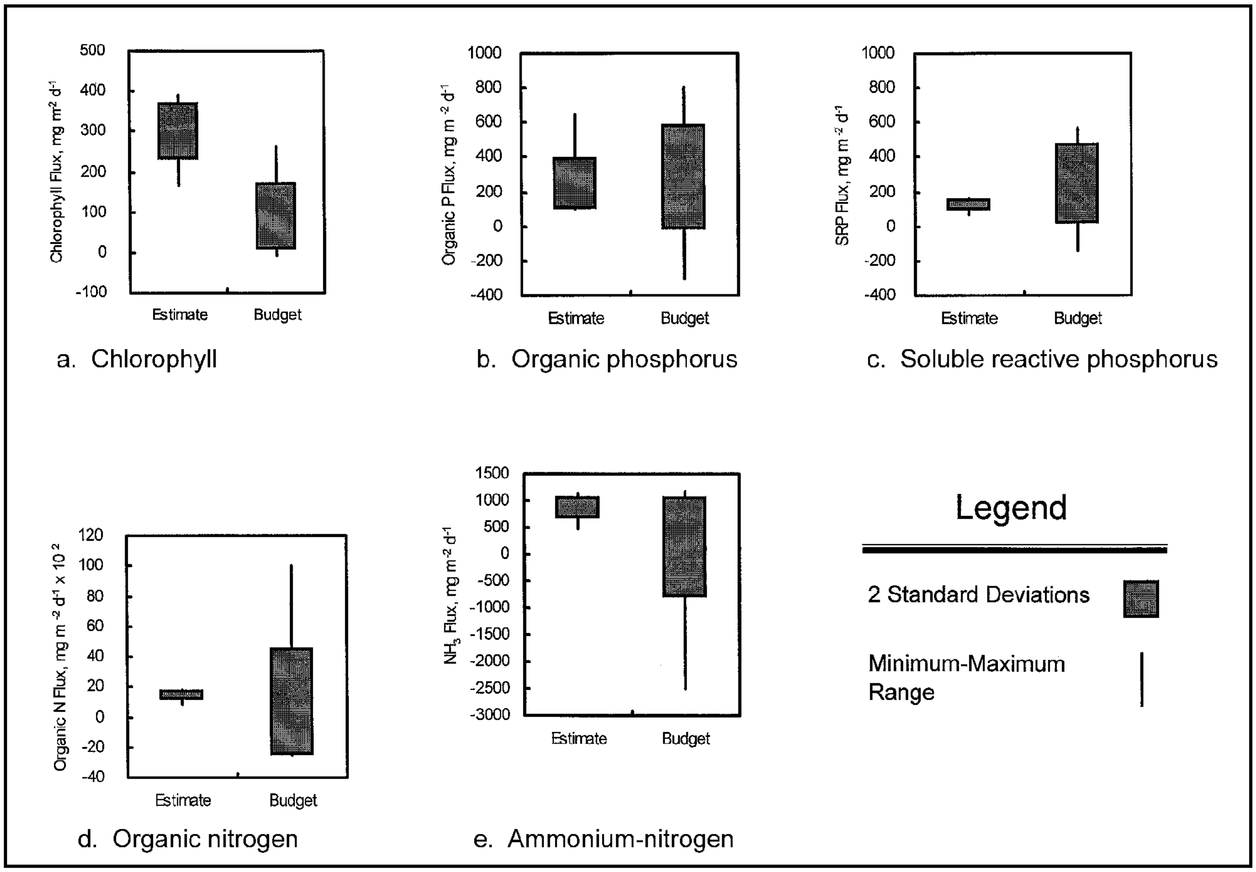


Figure 7. Comparison of fluxes (bar and whisker plots) determined via laboratory-based zebra mussel filtration and excretion rates (estimate) versus budgetary analysis of inflow-outflow changes (budget) in Harper's Ferry Slough. Chlorophyll, organic phosphorus, and organic nitrogen fluxes represent net retention in the system, while soluble reactive phosphorus and ammonium-nitrogen fluxes represent net export from the system

6b; Table 2), suggesting internal recycling and transformations of particulate nitrogen and phosphorus to soluble forms. Net export of soluble nitrogen and phosphorus was most likely due to zebra mussel activities in the slough, as others have demonstrated that zebra mussels can recycle substantial nitrogen and phosphorus via excretion (Heath et al. 1995; Arnott and Vanni 1996; James, Barko, and Eakin 1997).

Estimates of zebra mussel contributions to fluxes in the slough (i.e., filtration and excretion; Table 2), determined from length-frequency relationships, density estimates, and laboratory-derived filtration and excretion rates (i.e., Table 1), were compared with budgetary (i.e., inflow-outflow analysis) fluxes in order to identify potential impacts by zebra mussels on water quality. Estimated chlorophyll filtration by zebra mussels was nearly equivalent to the external chlorophyll load to the slough (Table 2); but it was higher than the mean net retention of chlorophyll in the slough, determined via budgetary analysis (Figure 7a). Discrepancies between estimated zebra mussel filtration and net retention of chlorophyll may be attributed to production of chlorophyll within the slough, which was not measured. Although the theoretical water residence time in the study reach was very low compared to reported doubling times of algae (Reynolds 1984), the western shoreline was extensively developed with docks, boat slips, boat houses, etc., that extended out

into the water. These structures may have altered water residence time along the western shoreline providing temporary refuge for algal production. Sloughing of periphytic growth from pylons located along the western shoreline may have contributed additional chlorophyll to the system.

Estimated zebra mussel filtration of organic nitrogen and phosphorus fell well within the range of budgetary estimates of organic nitrogen and phosphorus net retention in the slough (Figures 7b and 7d), suggesting that zebra mussel filtering activities were playing an important role in the retention of organic nitrogen and phosphorus in the system. In general, approximately 10 percent of the organic nitrogen and phosphorus load was retained within the system presumably via zebra mussel filtration activities (Table 2).

In contrast to net retention of organic nitrogen and phosphorus, there was net export of soluble forms of these constituents from the slough (Figures 7c and 7e). Although zebra mussels were estimated to contribute a substantial flux of NH_3-N to the system via excretion (Figure 7e, Table 2), budgetary analysis indicated much less net export of NH_3-N (Figure 7e) from the slough. The discrepancy may be due to oxidation of NH_3-N excreted by zebra mussels to nitrite-nitrate N by nitrifying bacteria in the slough. Although others have reported that the primary excretory form of nitrogen by zebra mussels is NH_3-N (Aldridge et al. 1995, Gardner et al. 1995, Heath et al. 1995), James et al. (1997) provided evidence that zebra mussel nitrogen excretory products were being converted to nitrate-nitrite nitrogen forms in laboratory microcosm experiments. When net export of nitrate-nitrite-N (Table 2) from Harper’s Ferry Slough was factored into the soluble nitrogen budget, the total soluble nitrogen net export rate of 719 $mg/m^{-2}/d^{-1}$ more closely reflected estimated nitrogen excretion rates by zebra mussels (Table 2).

Estimated zebra mussel excretion of SRP overlapped budgetary determinations of net SRP export from the system, suggesting that zebra mussels were contributing to the phosphorus economy of the slough (Figure 7c). Overall, external loading of SRP to the slough was substantial and dominated the phosphorus budget, as zebra mussel excretion accounted for only 10 percent of the measured SRP load (Table 2). However, estimated rates of phosphorus excretion by zebra mussels for Harper’s Ferry Slough suggested that zebra mussels recycled substantial phosphorus relative to other internal P fluxes measured in aquatic systems (Table 3). Thus, in aquatic systems receiving lesser external SRP loads, zebra mussel contributions are likely to play a much more substantial role in internal phosphorus recycling.

Table 3
Ranges in Rates of Internal Phosphorus Loading from Various In-lake Sources for a Variety of Aquatic Systems

Internal P Source	Rate, $mg/m^{-2}/d^{-1}$	Reference
Anoxic sediment P release	0.8 - 34.3	Nürnberg (1984)
Littoral zone	1.1 - 4.1	James and Barko (1991)
Groundwater	3 - 4	James and Barko (1993)
Zebra mussels (5,879 ind/m^2)	69 - 161	This Study
Zebra mussels (49,000 ind/m^2)	0 - 500	Effler and Siegfried (1994)

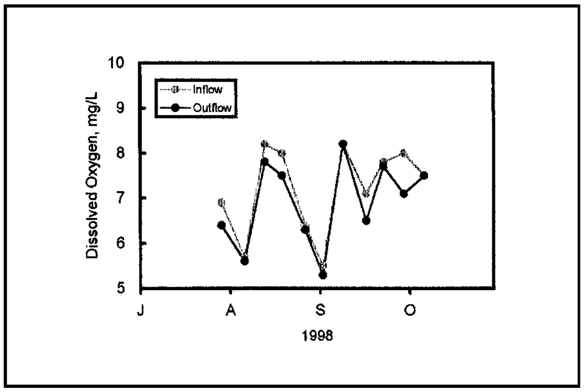


Figure 8. Variations in dissolved oxygen at the inflow and outflow stations of Harper's Ferry Slough

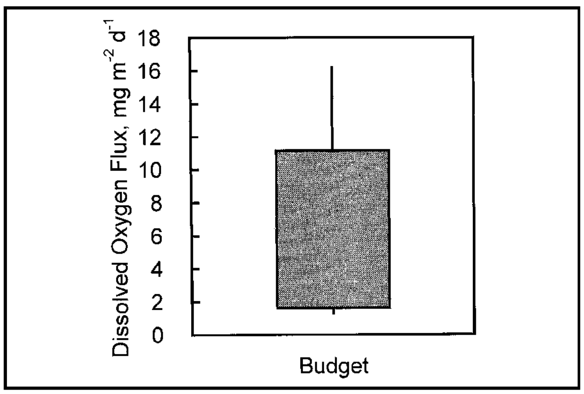


Figure 9. Bar and whisker plot of dissolved oxygen flux in Harper's Ferry Slough (grey bar represents two standard deviations; vertical lines represent minimum and maximum range of values)

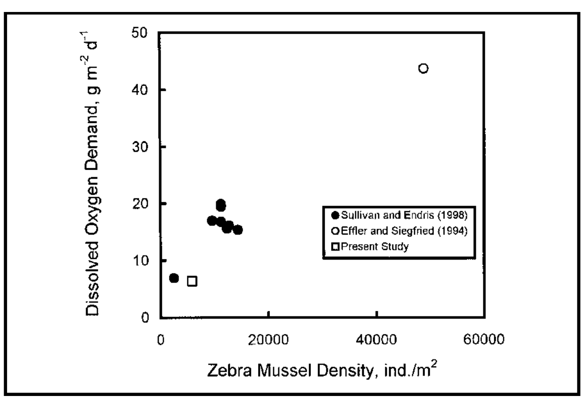


Figure 10. Zebra mussel density versus dissolved oxygen demand

Dissolved oxygen demand in the slough was also calculated through budgetary analysis (Table 2), as concentrations of dissolved oxygen were greater in the inflow than in the outflow of the slough (Figure 8). In general, the range in dissolved oxygen demand was large (Figure 9). When normalized with respect to average zebra mussel density in the slough, the mean dissolved oxygen demand of 6.4 $g/m^{-2}/d^{-1}$ fell within the range of demands reported by others for zebra mussel-infested systems (Figure 10). However, the rate in this study is perhaps underestimated because reaeration and net productivity were not considered in the calculations. Nevertheless, results suggest that zebra mussels were also impacting dissolved oxygen dynamics in Harper's Ferry Slough. Similarly, Effler and Siegfried (1994) and Effler et al. (1998) indicated that nearly the entire dissolved oxygen demand in a portion of the Seneca River colonized by high densities of zebra mussels could be accounted for by zebra mussel respiration.

SUMMARY AND CONCLUSIONS: Comparisons between empirical estimates of zebra mussel filtration and excretion and budgetary estimates indicated that zebra mussels, at a mean density of 5,879 ind./m^2, were having an impact on water quality conditions in Harper's Ferry Slough. Zebra mussel filtration estimates accounted for nearly all of the organic nitrogen and phosphorus retention in the slough. Similarly, zebra mussel excretion estimates fell within the range of SRP and soluble nitrogen export from the slough. Budgetary analysis of dissolved oxygen also indicated a substantial demand for oxygen stores in the slough, which was likely due to zebra mussel metabolic activities. Discrepancies between empirically estimated chlorophyll filtration by zebra mussels and chlorophyll retention in the slough may be attributed to production of chlorophyll within the slough. Increased light transparency created by zebra mussel filtration may have played a role in enhancing productivity in the slough (also see Caraco et al. (1997)).

In Harper's Ferry Slough and other aquatic systems, the magnitude of zebra mussel impacts on nutrient

recycling appears to be great, as rates of nitrogen and phosphorus excretion are considerably higher when compared to rates determined for other internal nutrient recycling pathways (i.e., Table 3; also see Arnott and Vanni (1996)). In particular, it appears that zebra mussels can rapidly transform particulate matter in the water column to soluble forms via filtration and excretion. Increased soluble nutrient loads, high oxygen demand, and increased light penetration as a result of zebra mussel colonization, may dramatically alter ecosystem dynamics in the Upper Mississippi River System and need to be considered within the framework of management and habitat rehabilitation.

ACKNOWLEDGMENTS: We gratefully acknowledge Shawn Weick and James T. Rogala of the U.S. Geological Survey, Upper Midwest Environmental Science Center for water sampling and bathymetric information; and Laura Blegen, Dale Dressel, Susan Fox, Charles Gruber, Michele Huppert, Kelly LaBlanc, Brenda Lamb, Emily Schneider, and Holly Wallace of the Eau Galle Aquatic Ecology Laboratory for chemical analyses of water samples.

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> James, W. F., Barko, J. W., Eakin, H. L., Hendrickson, J. S., Miller, A. C., and Sauer, J. (2000). "Nutrient recycling impacts by zebra mussels in Harper's Ferry Slough, Upper Mississippi River," *Water Quality Technical Notes Collection* (ERDC WQTN-PD-07), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes/army/mil/el/elpubs/wqtncont.html*

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